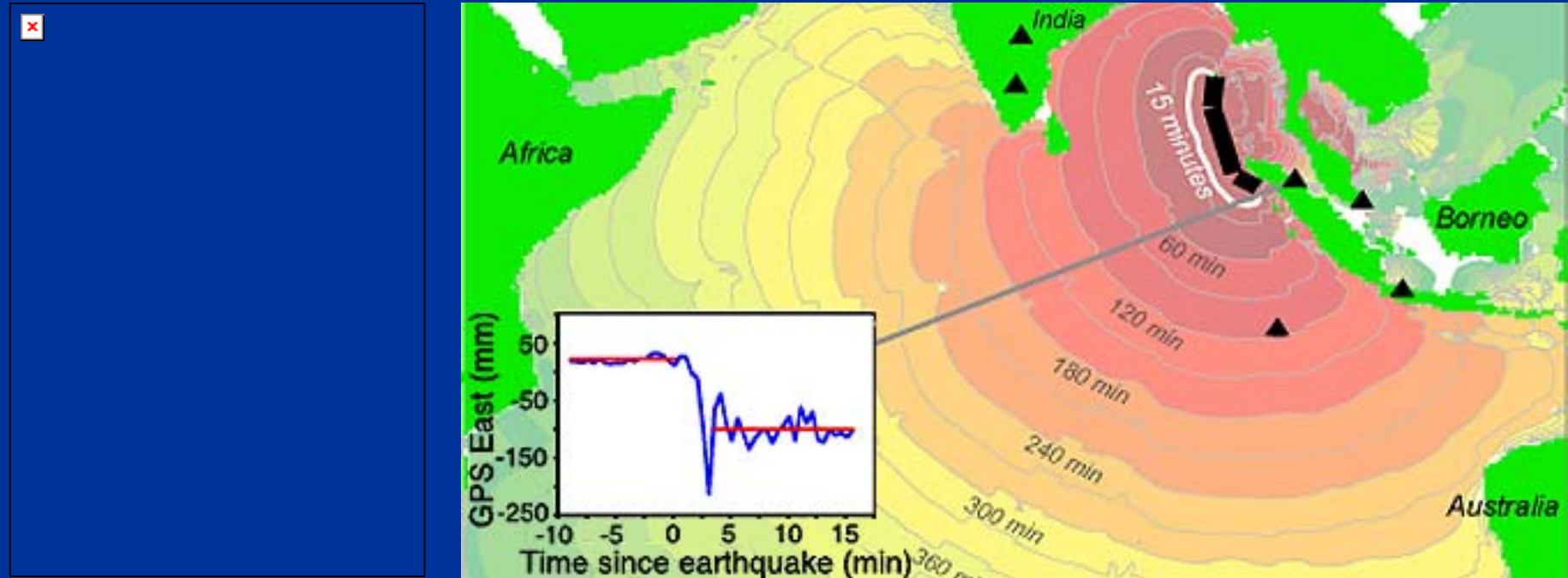


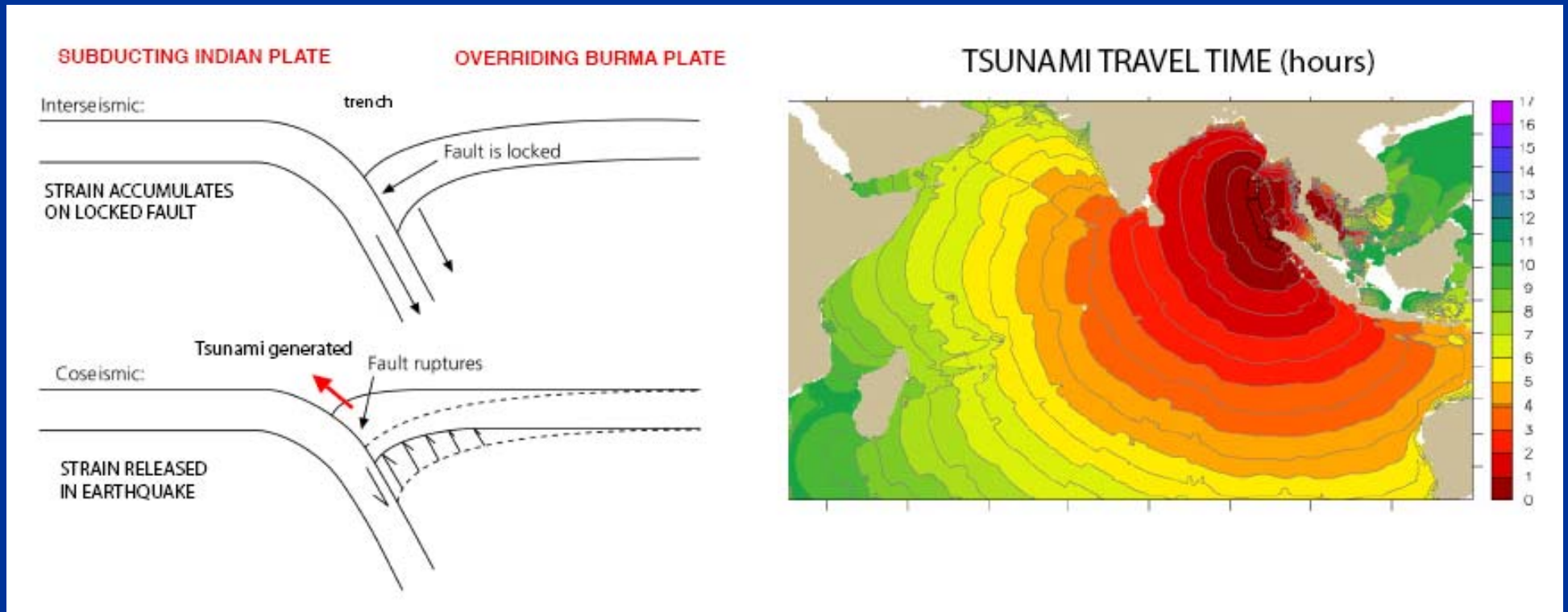
Toward Real-Time GPS for Tsunami Warning Systems and Post-Earthquake Damage Assessment and Emergency Response



Geoff Blewitt, Corné Kreemer, Bill Hammond, Hans-Peter Plag , Seth Stein, Emile Okal, Yoaz Bar-Sever, Richard Gross, Vindell Hsu, Kenneth Hudnut, Mark Simons, Tony Song, and Frank Webb

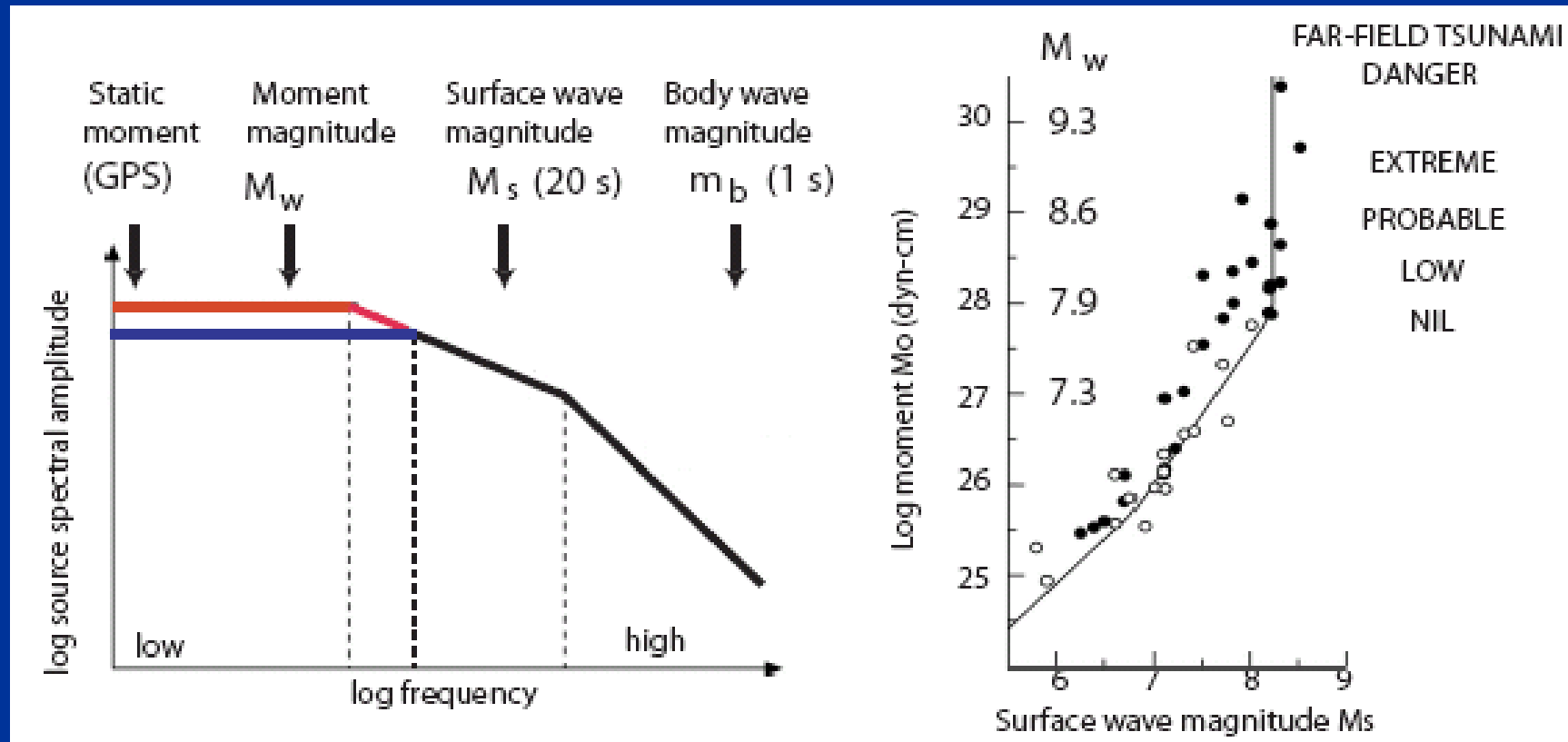
University of Nevada Reno
Northwestern University
Jet Propulsion Laboratory
NOAA/NWS, USGS, and Caltech

Oceanwide Tsunami Warning: The Challenge



- First hour is important for early warning of oceanwide tsunamis
- Tsunamigenic potential directly relates to seismic moment
 $\sim (\text{fault slip}) \times (\text{rupture length}) \times (\text{rupture width})$
- **Underestimation of seismic moment for great earthquakes compromises early warning** (Kerr, 2005; Menke and Levin, 2005)

Seismic Magnitude Saturation: A Major Obstacle to Early Warnings



- Early seismic magnitudes saturate at 8–8.3 (Geller, 1976)
 - but oceanwide tsunamis typically require $M_w > 8.5$
- But $M_w > 8.0$ can be given accurately & early using GPS

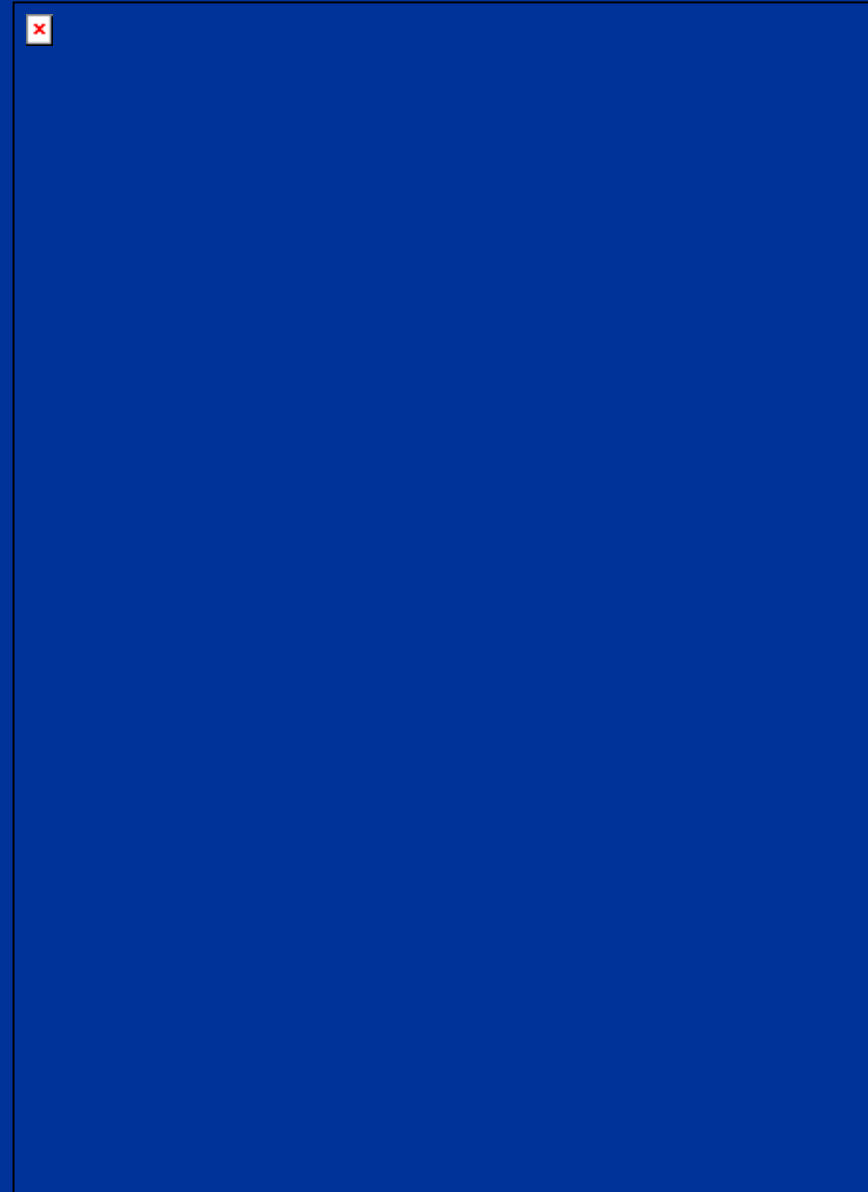
GPS Seismology vs Seismograph



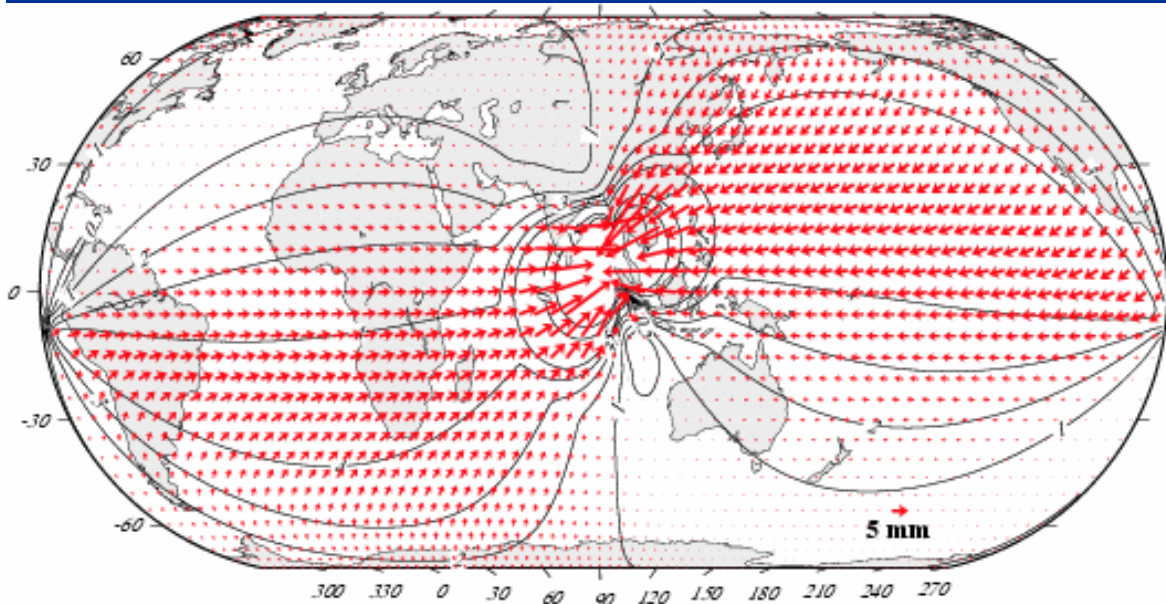
- x 10–100 sensitivity for long periods

New Concept: GPS Displacement Method

- **Before Earthquake**
 - Plates are locked as stress builds up
 - GPS station located on the overriding plate
- **During Earthquake**
 - Plates slip by meters
 - Vertical motion of ocean floor causes tsunami
 - GPS station displaced
 - Invert GPS data for earthquake slip model
 - Input to tsunami model

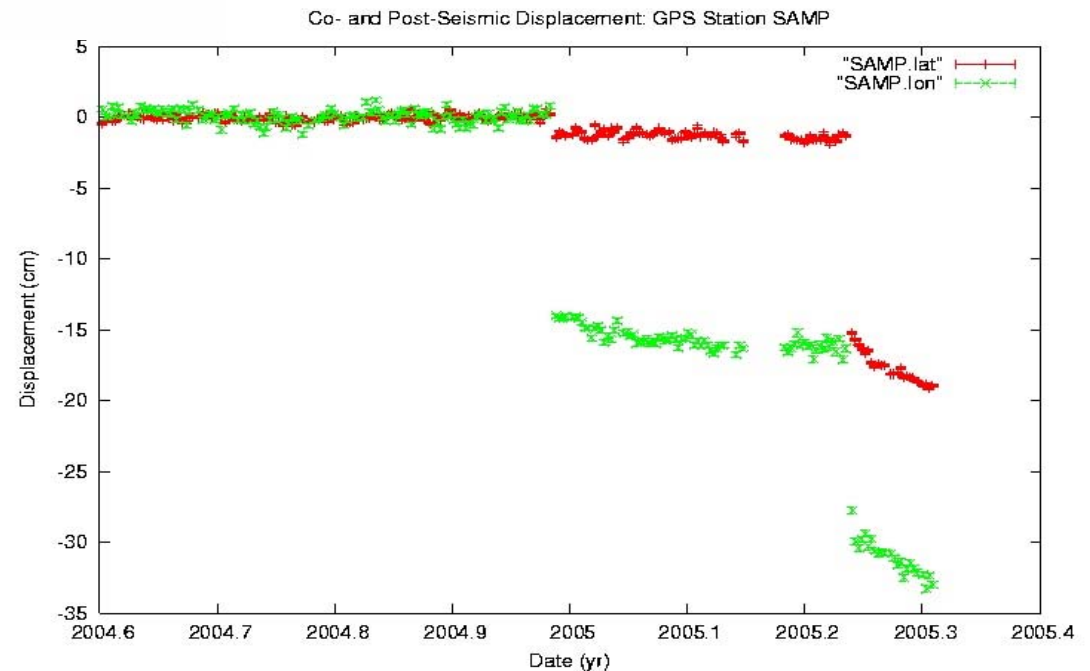


2004 Sumatra Earthquake Displacements



- Post-event estimation of displacement field
 - global deformation!
 - > 10 mm as far as India

- Daily time series confirm the permanent component of deformation
 - “truth” to assess real-time systems



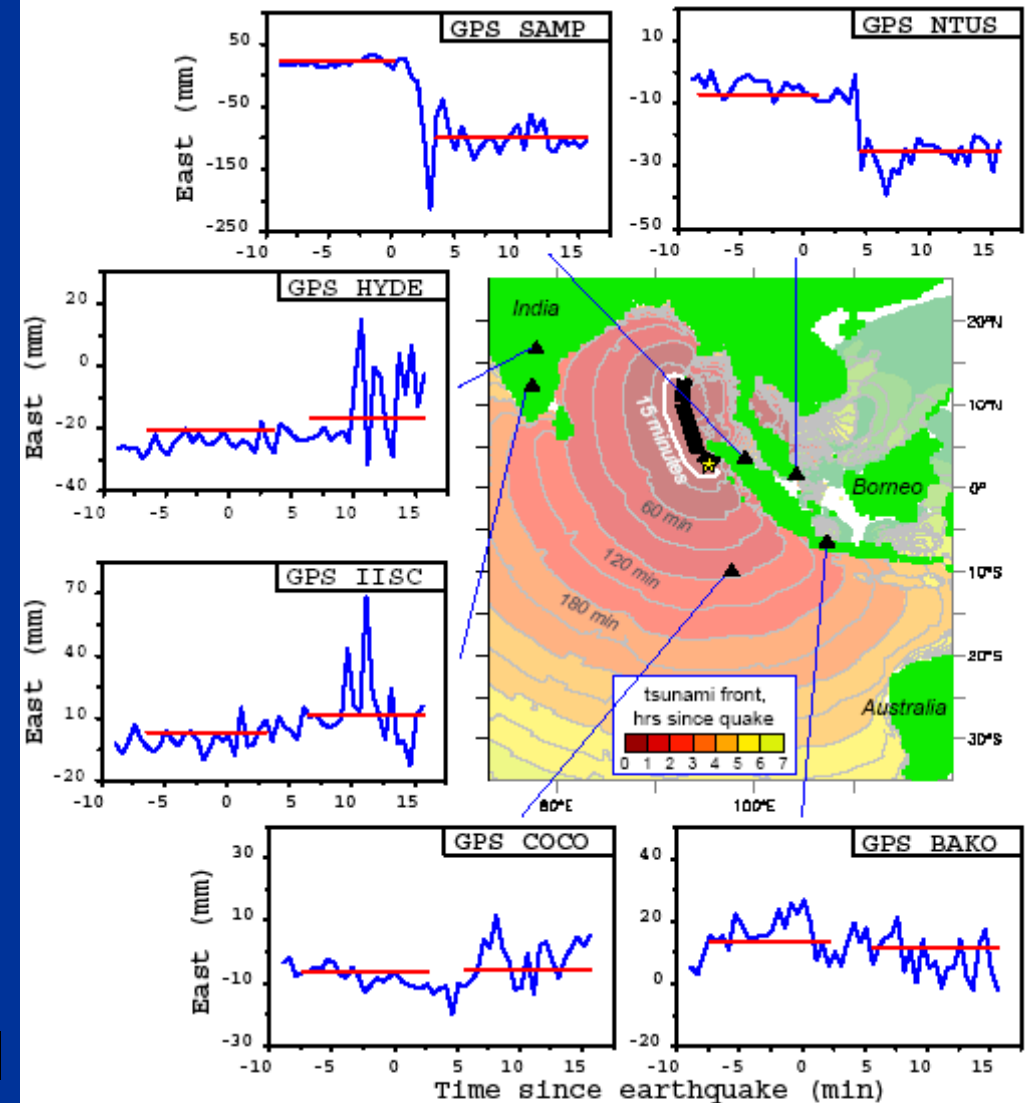
GPS Data Processing Strategy

- Simulate real-time situation
 - only use information that can be available in real time
 - 24 hours of 30-sec data up until 20 minutes after origin time
- Estimate parameters accurately
 - GPS satellite and station clocks
 - Station positions
 - every 30 sec if $< 3,500$ km from source
 - as constant if $> 3,500$ km from source
 - Earth's pole position and rate of rotation
 - Tropospheric zenith delay and gradients (random walk)
 - Multipath repeats with \sim sidereal period
 - Errors reduced by applying a sidereal filter

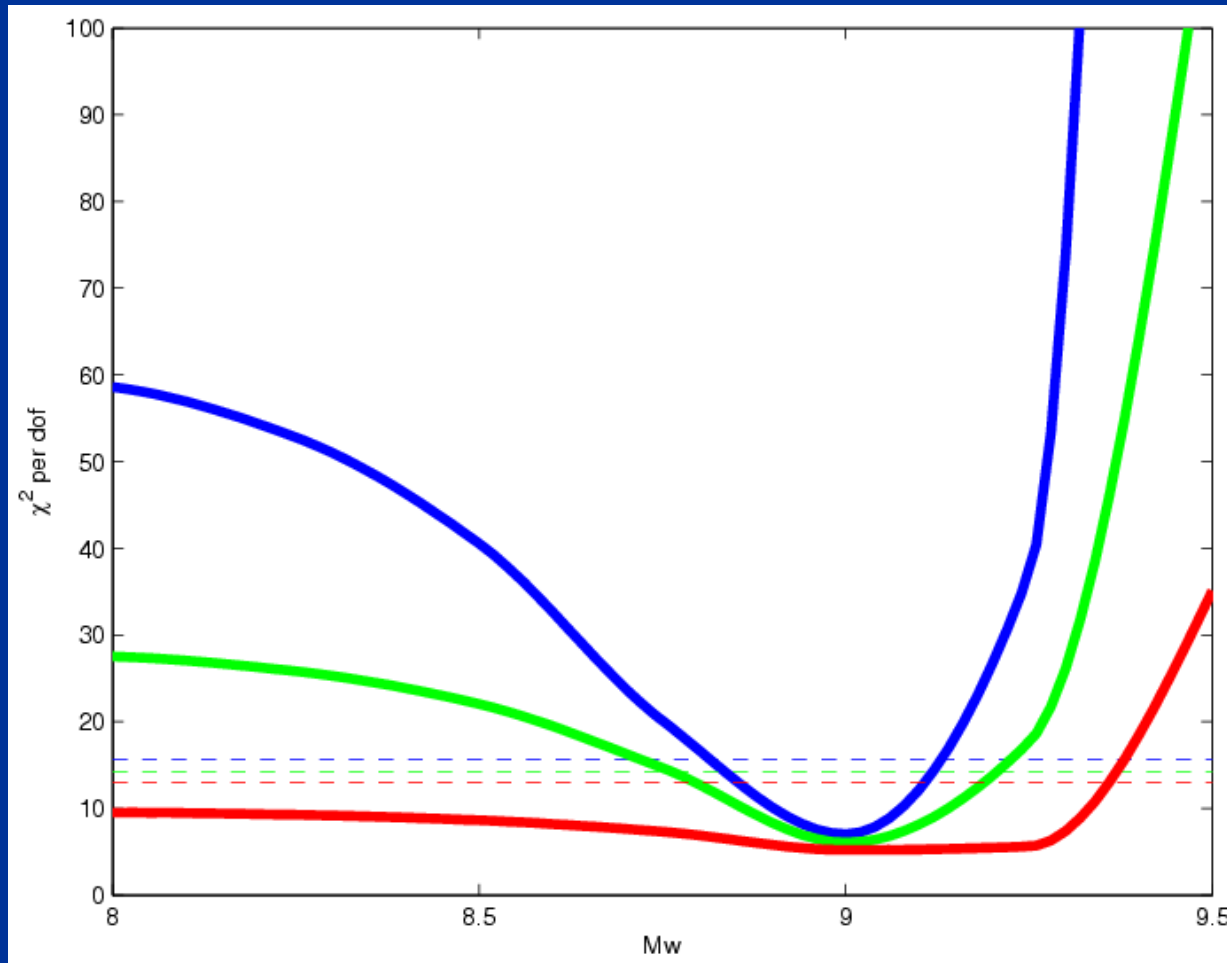
GPS Results

- Using estimated orbits
- Rapid displacement
 - Data confirm that it arrives mostly with body waves
 - Can be resolved using 15-minutes after the quake
 - Accuracy ~ 7 mm
- Can be used to estimate earthquake slip model
 - Model displacements ~ 3 mm
- And keep in mind...
 - Network was far from optimal

GPS 30-sec Series



Rapid Moment Magnitude Estimation by GPS



- Best fit models:
 $M_w = 8.9 - 9.1$
rupture = 1000 km
- Blue
 - using all sites
- Green
 - no SAMP (300 km)
- Red
 - no SAMP (300 km)
 - no NTUS (900 km)

Tsunami Magnitude Scale

$$S_T = 2 \times (\log_{10} \sqrt{E_T} - 5) \equiv \log_{10} E_T - 10$$

- Seismology \Rightarrow earthquake location + time
- Fault database \Rightarrow slip geometry scenarios
- GPS displacements \Rightarrow earthquake source model
 - \Rightarrow sea floor motion
 - \Rightarrow vertical + horizontal motion
 - \Rightarrow potential + kinematic energy
 - \Rightarrow tsunami energy E_T
- Wave amplitude $\sim \sqrt{E_T}$
- Tsunami scale $S_T > 5$ for oceanwide tsunami

Simulation: Tsunami Warning Threshold

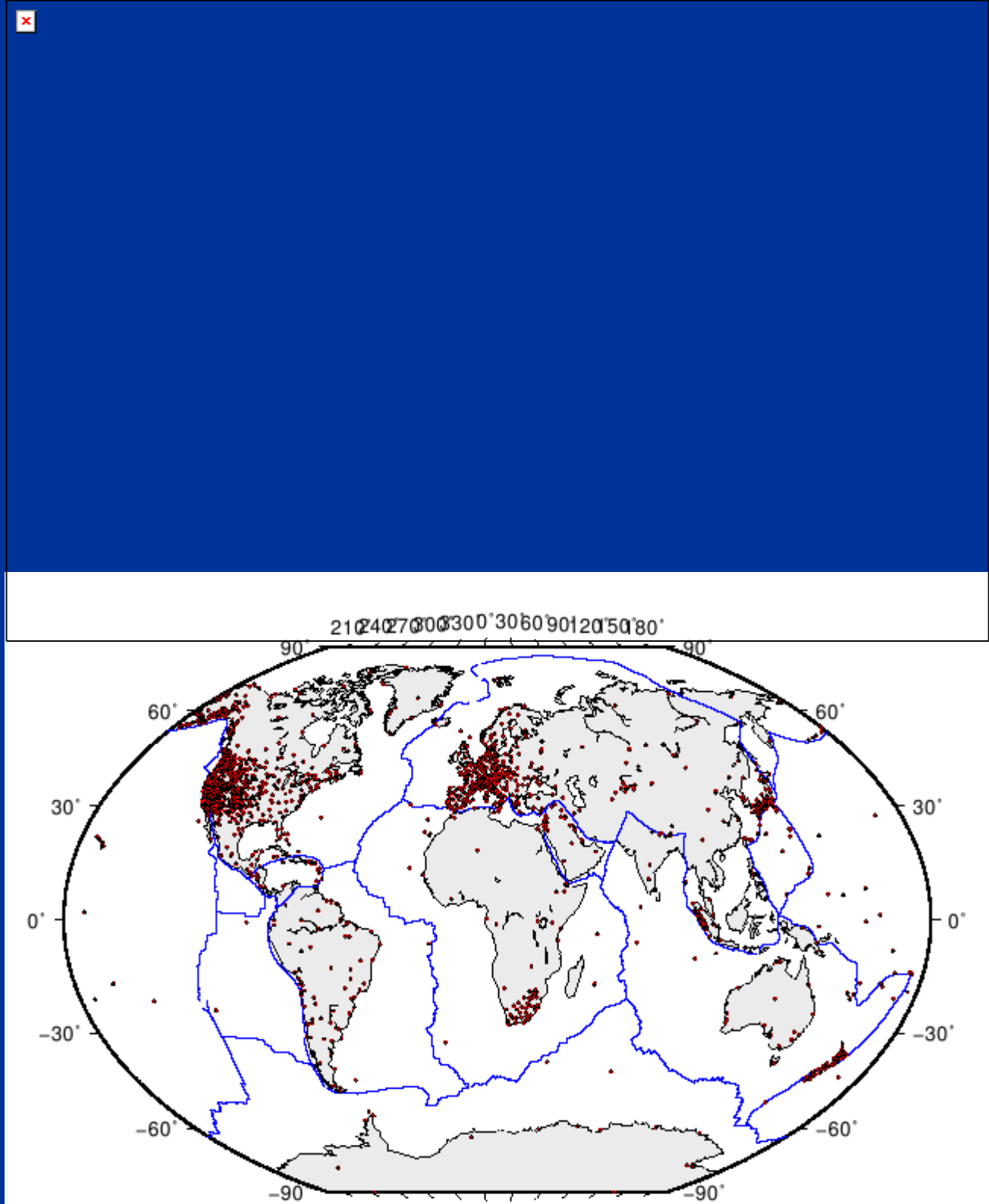
Earthquake Magnitude	Tsunami Energy E_T		Tsunami Scale S_T		Issue Warning?
	GPS	Seismic	GPS	Seismic	$S_T = 5$ threshold
2004 Sumatra M_w 9.2	6.0e+15 J	5.2e+15 J	5.8	5.7	>> 5 Yes
1964 Alaska M_w 9.2	8.2e+15 J		5.9		>> 5 Yes
2005 Nias M_w 8.7	2.8e+14 J	2.2e+14 J	4.4	4.3	<< 5 No



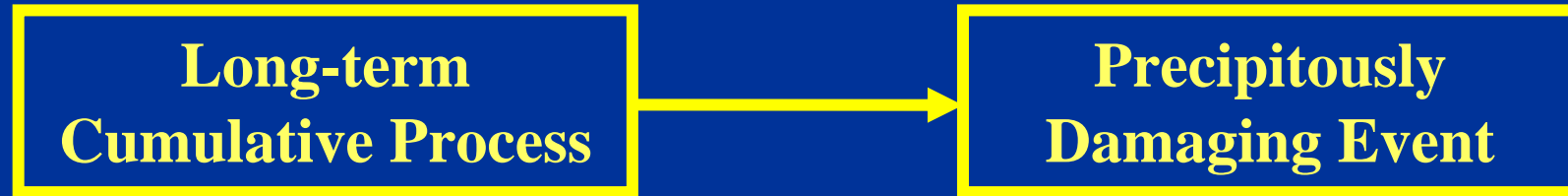


Regions at Risk

- 100 years of great earthquakes
- $M_w > 8.5$ can create oceanwide tsunami
- GPS network today:
 - 2000 stations
 - plus ~2000 in Japan!
- Many ideally located
 - EarthScope's Plate Boundary Observatory
- Many holes to fill



Nature of (Many) Geohazards



Nature of (Many) Geohazard Investigations



There's got to be a better way...



The Early Warning Dilemma and Solution

- **Where?**

- Deploy LONG TERM prediction/monitoring networks to inform the deployment of early warning systems, tied to ITRF reference frame

- **When?**

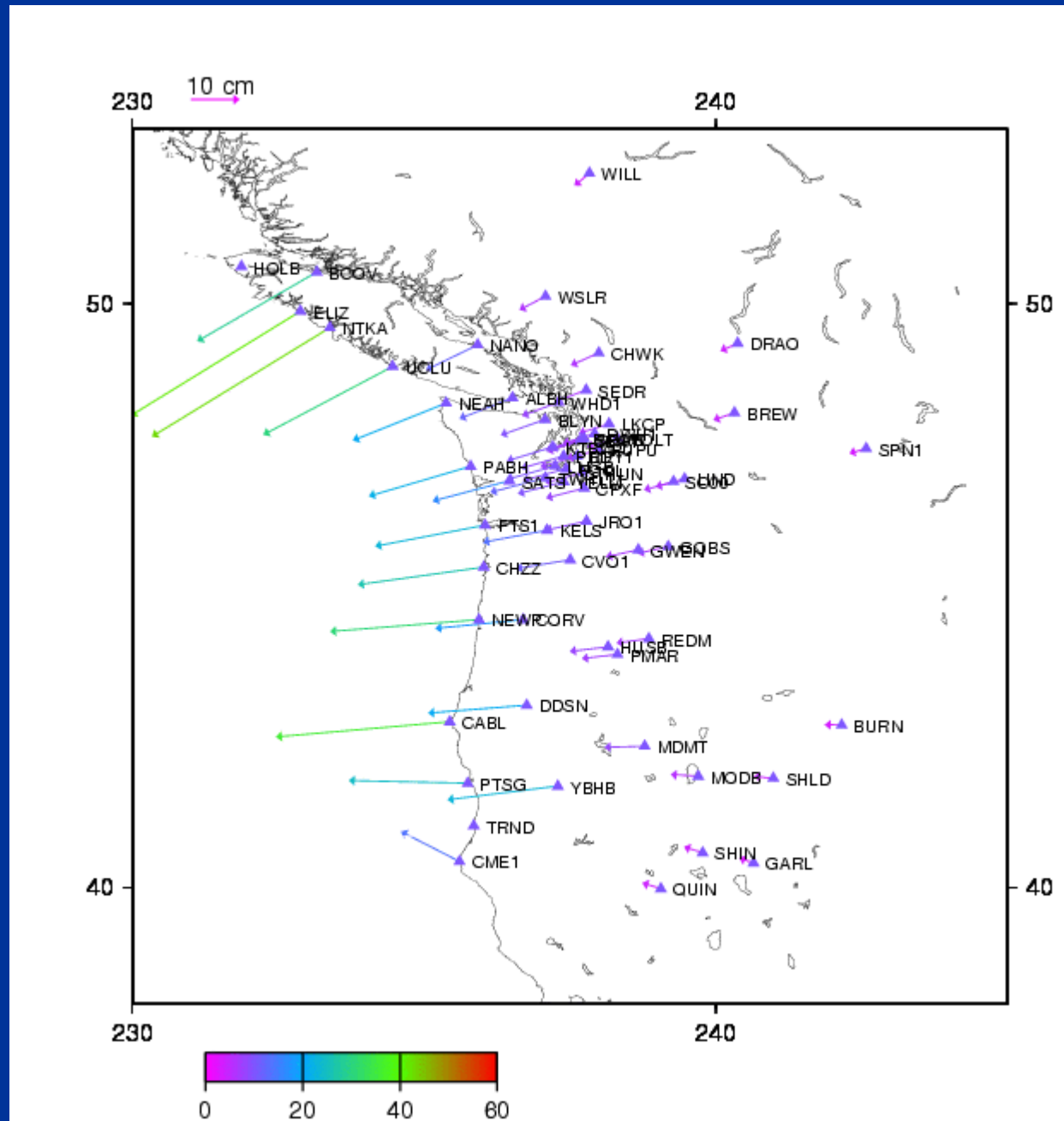
- Early warning systems need to be deployed BEFORE the disaster hits!

- **How?**

- Prediction Network = Early Warning Network

Prediction Networks ↔ Early Warning Networks

- Example:
 - Cascadia Subduction Zone
 - EarthScope/PANGA
 - Simulation of Mw 9.0 quake
 - ~10 cm static displacements
- Recommend:
 - Upgrade network to real time



Recommendations

- Real-time GPS/GNSS should be integrated into current geohazard early warning systems to add value to existing technologies
- Early warning networks need to be deployed before disasters strike. Deployment needs to be informed by prediction systems. In the case of geodesy: make the two systems the same.
- GGOS should provide the reference frame and a real-time positioning service for geohazard early warning systems
- National and international coordination and support are required for planning, research, and development of such upgrades
 - US national agencies are starting to coordinate plans
 - NASA, USGS, NOAA, and university researchers